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RESEARCH MEMORANDUM

AN EXPERIMENTAL EVALUATION OF SEVERAL DESIGN VARIATIONS OF HOLLOW TURBINE BLADES FOR EXPENDABLE ENGINE APPLICATION

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Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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RESEARCH MEMORANDUM

AN EXPERIMENTAL EVALUATION OF SEVERAL DESIGN VARIATIONS OF HOLLOW TURBINE BLADES FOR EXPENDABLE ENGINE APPLICATION

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SUMMARY

An investigation was made to evaluate several design variations of hollow turbine blades intended for missile-engine use. In one general type, the airfoils were formed from sheet metal; in a second type, the blades were cast. The blades were operated in a J47 engine at 7950 rpm turbine speed and 1260° F tail-pipe temperature until a failure occurred or a service life of 30 hours had been attained.

It was determined that a practical missile turbine blade can be made by either method of fabrication. In addition, useful data were obtained on root fastenings for application to light-weight rotor design.

Blades with Sheet-Metal Airfoils

Three sheet materials were investigated: L-605, Hastelloy B, and A-286. Airfoils made from L-605 and Hastelloy B satisfied the test requirements; A-286 proved to be somewhat less satisfactory because of susceptibility to cracking.

It was found that a practical method of fabrication consisted of forming the airfoil sides separately and joining them by welding along the leading and trailing edges. Forming from a tubular shape was unsatisfactory in the case of the L-605, but favorable results were obtained with Hastelloy B.

The effect of wall thickness was investigated and it appeared that 0.030 inch was a practical minimum dimension, even in the tip region of tapered walls. The wall-thickness tests were made only with L-605 but the results probably will have a general application because the factors of structural rigidity and resistance to fatigue are involved.

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Attachment between airfoil and base was made by welding or brazing. Brazing was found to be superior to welding.

Cast Blades

Hollow blades cast from HS-21 appeared to be slightly superior to blades of X-40. The airfoil walls were tapered, 0.055 inch at the base to 0.030 inch at the tip. The HS-21 blades were operated in the as-cast condition; it was found that X-40 required heat treatment and shot- 3563
peening of the root serrations in order to obtain reasonable service life. The X-40 blades displayed a tendency toward tip failure in fatigue.

The root modification used for cast-blade specimens was found to be more satisfactory than the design used with sheet-metal airfoils.

INTRODUCTION

A research program has been in progress at the Lewis laboratory to investigate the possibility of designing hollow turbine blades and light-weight rotors for expendable missile engines. The specific purpose of the research described in this present report was an experimental evaluation of a number of hollow turbine blades intended for short service life. It was considered that a blade service life of approximately 10 hours would satisfy the requirements for missile-engine application. In order to evaluate reliability, however, it was decided to fix the minimum endurance time at 30 hours.

Two general types of hollow blades were considered in this investigation; several variations of each type were made. In one type, the airfoils were made from sheet-metal stock and attached to separate bases; in the second type, the entire blade was formed by casting.

The results of a previous investigation of sheet-metal airfoils are given in reference 1; it appeared that L-605 sheet stock had favorable characteristics for missile-engine application. In the present program it was intended that further investigation should be made of L-605, and that the scope of the research should include consideration of other sheet-metal alloys. The materials A-286 and Hastelloy B were selected. The characteristics of these alloys were considered favorable, and the amounts of strategic alloying elements present in these materials are somewhat lower than L-605.

In the case of the cast blades, HS-21 and X-40 were selected on the basis of known strength at elevated temperature and facility in casting. The compositions of the sheet materials and cast alloys included in the hollow-blade investigation are shown in table I.

Airfoils made from the sheet materials were attached to the bases by brazing or welding. The J47 airfoil configuration was used. There were fourteen variations among the sheet-metal blades. These variations consisted of differences in material, methods of fabrication, and geometric shape of root.

The purpose of including tests of different root shapes was to obtain data for application to the design of light-weight turbine rotors. The cast blades were made by the lost-wax process. There were four variations of this type. In addition to the investigation of two different alloys, attention was given to effects produced by heat treatment, different root shapes, and shot-peening of the root. The airfoil shape differed in some degree from the standard J47 blade. Chord.thickness was greater at the tip.

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The finished turbine blades were installed in a standard turbine wheel and operated at maximum service conditions of tail-pipe temperature and turbine speed. Operation was continued until failure occurred or a specimen had attained a life of 30 hours.

CG-1 back

DESCRIPTION OF BLADES

The sheet-metal airfoils conformed in shape to the standard J47 design; in the case of the cast blade, the airfoils had less external taper in order to provide for a casting core of adequate strength. Aerodynamic analysis indicated that this condition would have some effect on turbine performance, but it was considered that the reduction in turbine-passage area would not be detrimental.

The variations among the blade groups are given in table II. The number of sample blades of each design was not the same; the size of sample groups was determined on the basis of previous bench-test results, relative importance, and the immediate availability of materials.

Blades with sheet-metal airfoils. - In two of the design groups the airfoils were formed from seam-welded tube. The seam fell outside the trailing edge after the forming operation had been completed. The trailing edge was then brazed and the portion containing the seam was cut off. Braze was introduced into the leading edge also in order to alleviate the effect of possible cracks.

The other sheet-metal airfoils were made in two parts. The suction and pressure sides were formed in separate dies. The pressure-side dies are shown in figure 1. In a subsequent operation the two sides were welded together along the leading and trailing edges.

The hollow airfoils were attached to bases and the tips were closed by a welded or brazed cap. The purpose of the cap was to prevent a type of tip vibration characterized by independent wall movements. The two types of caps are shown in figure 2.

Standard J47 turbine bases were modified as required for the investigation. Four types of bases were used. These are shown in figure 3. In base A, the solid airfoil was removed to a height of 0.13 inch above the base platform. This 0.13-inch stub was then machined to fit the inside of the hollow airfoil. A second design, base B, was similar with the exception that a considerable part of the serrated root was removed. In the base C design, the solid airfoil was removed flush with the base platform. The fourth design type, base D, had as design characteristics the flush platform and the modified root. In most cases, a vent was provided in the base, in order to avoid the possibility of moisture being sealed within the completed blade. 3563

There were several variations in the geometry of the base attachment. In certain design groups the airfoil was brazed to a base stub; in others, the airfoil was welded to a flush base. An exception to both these methods was attachment by braze in tension. A contoured slug 0.19 inch in length was brazed inside the airfoil base. The end was machined flat and then the completed airfoil was brazed to a flush base. Figure 4 shows this construction.

Figure 5 shows the method of locating an airfoil on a base. Small tack welds were used to maintain this position. Attachment was completed by welding or brazing. The heliarc process was used in welding; rod of the same material as the airfoil was employed. Helium was directed into the interior of the airfoil during welding to provide an inert atmosphere.

The brazing material was Nicrobraz, with nickel addition in some cases. Detailed information on Nicrobraz and its application is presented in reference 2. Most of the brazing was done in a vacuum furnace. In the case of one airfoil material, A-286, the process was carried out in a salt bath because of the presence of titanium in the alloy. This was followed by heat-treating the material for 16 hours at 1325° F.

Three materials were used for airfoils, L-605, A-286, and Hastelloy B. The L-605 airfoils were made in more than one wall thickness and in several wall tapers. Stock was available in 0.030 and 0.060 inch. Material of less than 0.030 inch was made by rolling. Tapered stock was obtained by machining. The machining stresses were relieved by a heat-treatment of 1 hour at 2225° F. Hastelloy B was available in 0.060-inch thickness; this material was reduced to the required 0.030-inch thickness by rolling.

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Cast blades. - These blades were made by the lost-wax process. Two materials were used in the investigation, X-40 and HS-21. Blades made from X-40 were tested in the as-cast condition and also in the heat-treated condition with shot-peening of the root. Table III describes the heat treatment. The HS-21 blades were operated in the as-cast condition.

The construction of the cast blade is shown in figure 6. Two types of base were used. The bases are shown in figure 7. The purpose of using the modified root design was to obtain data for light-weight rotor application.

EXPERIMENTAL PROCEDURE

The specimen blades were operated in a J47 engine. Twelve blades were tested simultaneously, spaced at equal intervals around the turbine rotor, with standard solid blades making up the remainder of the turbine blade complement. Little difficulty was experienced in obtaining moment-balanced pairs of blades with modified roots; in the case of the standard blades it was necessary to remove material from some of the bases in order to obtain moment-balanced pairs. Moment balance has reference to location of blade mass center with regard to the turbine axis. A thin replaceable shroud section in the tail cone was used to reduce the effects of impact damage attendant on a blade failure.

The procedure of engine operation consisted of gradual acceleration to a turbine speed of 7950 rpm. Tail-pipe temperature was adjusted to 1260° F. Operation was continued until a failure occurred or until the hollow blades had accumulated at least 30 hours at the stated conditions.

RESULTS AND DISCUSSION

The results of the investigation are presented in figure 8. The order of listing is not chronological in all cases.

Groups 1 to 14, inclusive, of the table include the blades with sheet-metal airfoils. Groups 15 to 18 compose the cast-blade specimens.

For convenience in discussion the design groups will be considered separately.

Group 1. - (L-605, 0.030-in. wall, all-welded, fig. 3, base D.) All of the six specimen blades failed in less than 10 hours. The immediate cause of failure was deformation in the base. Figure 9 shows the type of failure. It was noted also that the weld penetration was not uniform in the base attachment. The results indicated that this type of base is of insufficient strength and that the relative disparity in mass between the airfoil and the base is unfavorable for welding.

Group 2. - (L-605, 0.030-in. wall, all welded, fig. 3, base C.) In this group of blades the importance of sound welding was exemplified. All six blades failed because of imperfect weld penetration; four blades failed in less than five hours. Figure 10 shows typical failed specimens. Automatic machine weld might prove to be more effective in making joints of this type. 3563

Group 3. - (L-605, 0.030-in. wall, welded airfoil brazed to stub, fig. 3, base B.) The failure of three blades was attributed to improper fabrication. Excessive clearance between the pressure side of the airfoil and the stub resulted in an inadequate braze. Another blade failed because of a crack that originated in the trailing edge. Two blades were operated for about 18 hours before failure occurred due to base deformation. The failures were similar to those that were characteristic of the group 1 tests. The stub section did not provide sufficient stiffness to the modified base. Location of the root supports at points nearer the center of the blade platform would result in a more favorable stress distribution. One of the base failures is shown in figure 11.

Group 4. - (L-605, 0.030-in. wall, brazed tip cap, welded airfoil brazed to stub, fig. 3, base A.) Two blades of this group failed because of improper fabrication. The remaining four specimen blades completed 30 hours. The failure presented in figure 12 shows a typical example of excessive clearance, approximately 0.060 inch between surfaces. Clearance should be 0.001-0.004 inch for best results. The results indicate that attachment of a tip cap by brazing is feasible. The failures caused by excessive clearance between brazing surfaces are not of great significance; in subsequent fabrication the technique was changed and there was only one recurrence.

Group 5. - (L-605, 0.025-in. wall, welded airfoil brazed to stub, fig. 3, base A.) One blade failed as a result of excessive clearance in the brazed attachment. Three blades were removed from testing because of failure in the airfoil at the midsection. Two blades were still intact after 30 hours of operation. The failures appeared to be the result of fatigue. Figure 13 shows a representative failure in the airfoil midsection.

Group 6. - (L-605, 0.022-in. wall, welded airfoil brazed to stub, fig. 3, base A.) Failure occurred in less than 10 hours of operation for the six blades of this group. Serious cracking or actual rupture in the airfoils occurred near the base, the midsection, and the tip. Figure 14 presents typical failures. It is probable that the decrease in structural rigidity caused by the relatively thin airfoil wall made this type of blade particularly susceptible to vibration.

Group 7. - (L-605, 0.030-in. wall, welded airfoil brazed to flush platform as shown in fig. 4, fig. 3, base C.) The three specimen blades were intact at the end of 30 hours of operation. The results indicated that it would be practical to use a brazed joint in tension for the base attachment.

Group 8. - (L-605, 0.030-in. wall, airfoil formed from tubular stock brazed to stub, fig. 3, base A.) Five of the blades tested were undamaged after 30 hours of operation. Seven were withdrawn from the
3563 test after sustaining tip failure. Two blades failed near the base, and another blade received excessive impact damage. The majority of the failures originated in the leading or trailing edge, probably as a result of severe bending during fabrication or of inadequate trailing-edge brazing. Two of the failures are shown in figure 15.

Group 9. - (Hastelloy B, 0.030-in. wall, airfoil formed from tubular stock brazed to stub, fig. 3, base A.) There were no failures among the six blades of this group during the 30-hour period in the engine. The results indicated that forming of airfoils from tubular stock is a satisfactory method. It was shown that Hastelloy B is a practical material for expendable turbine blades.

Group 10. - (A-286, 0.030-in. wall, welded airfoil salt-bath brazed to stub, fig. 3, base A.) One blade survived 29 hours of operation before removal from the test because of cracks in the airfoil tip. Three other blades sustained similar failure in shorter operation times. One blade failed in the base as a result of defective brazing. The clearance between parts was correct but the braze material had not filled the joint. The results show that A-286 blades are relatively susceptible to tip fatigue. In addition, it is probable that special welding and brazing techniques are required. The salt-bath brazing was not entirely satisfactory. Figure 16 shows typical failures.

Group 11. - (L-605, 0.030 to 0.020 in. tapered wall, welded airfoil brazed to stub, fig. 3, base A.) Cracking in fatigue after short engine life characterized the failures of the six sample blades. Typical examples are shown in figure 17. The failures occurred at several locations along the airfoil. It appeared that the tapered wall was of insufficient thickness to resist vibration.

Group 12. - (L-605, 0.035 to 0.020 in. tapered wall, welded airfoil brazed to stub, fig. 3, base A.) Three blades of this group failed in less than 10 hours of operation. The failures were all in the tip region, and were attributed to fatigue. It is possible that a welding problem exists where it is necessary to join comparatively thin sheet. On the other hand, slight variations in the machined taper may have been a critical factor. Figure 18 shows the type of failure encountered in operation. The other three blades were still in good condition at the end of 30 hours in the engine. On the basis of these results it appeared that the wall thickness in the tip is an important factor in a design that employs tapered airfoil walls.

Group 13. - (L-605, 0.040 to 0.020 in. tapered wall, welded airfoil brazed to stub, fig. 3, base A.) There were five blades in this sample group; only one blade failed within the 30-hour test period. This failure occurred in the tip region after more than 29 hours and appears in figure 19. From the appearance of the failure it appeared that the crack originated in the weld. The results indicate that the proper design of tapered airfoil walls may produce satisfactory turbine blades.

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Group 14. - (L-605, 0.050 to 0.030 in. tapered wall, welded airfoil brazed to stub, fig. 3, base A.) The eight blades of this type completed 30 hours in the engine with no failures. There was no evidence of incipient cracking in the airfoils or in the base attachment. These blades were formed from the relatively thick tapered stock; apparently this was a more nearly optimum design.

Group 15. - (X-40, 0.055 to 0.030 in. tapered wall, cast, modified base.) The six blades of this group were removed after 9 hours. One blade had failed in the root serration and three others showed serious cracking in this region. The two remaining blades had developed cracks in the airfoil as well as in the root. The evidence indicated that the blades of this group were subject to fatigue failure. Figure 20 shows the root-serration failure.

Group 16. - (X-40, 0.055 to 0.030 in. tapered wall, cast, standard base.) At the end of 20 hours of engine life the sample of four blades was removed. Three of the blades had developed fatigue cracks in the tips; the fourth blade also appeared to be cracked by vibration, but may have been damaged by impact. Typical failure is shown in figure 21. The X-40 blades in the as-cast condition are susceptible to fatigue.

Group 17. - (X-40, 0.055 to 0.030 in. tapered wall, cast, heat-treated, shot-peened modified base.) After 24 hours of operation four of the eight sample blades were removed. These blades had fatigue cracks in the tips. The remaining four blades survived 30 hours of operation, although inspection of the bases revealed evidence of cracking in the root serrations. Figure 22 shows one of the failures. A comparison of these results with those obtained from the group 15 tests indicates that considerable improvement in the quality of X-40 cast blades can be obtained by proper heat-treatment and work-hardening of the root. There was less tendency toward tip failure by fatigue, and root-cracking was reduced.

Group 18. - (HS-21, 0.055 to 0.030 in. tapered wall, cast, modified base.) The sample of four blades completed 30 hours. The airfoils were in good condition but inspection showed some evidence of incipient fatigue cracking in the roots. Some impact damage occurred from failures of other test blades but not of such magnitude to render the blades inoperable. The greater ductility of HS-21 under impact compared to that of X-40 is a favorable characteristic for hollow turbine-blade application.

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SUMMARY OF RESULTS

An experimental investigation was made to evaluate several design variations of hollow turbine blades; in one general type, airfoils were formed from sheet metal; in a second type, the blades were cast. The blades were operated in a J47 engine at 7950 rpm turbine speed and 1260° F tail-pipe temperature until failure occurred or a service life of 30 hours had been attained.

It was determined that a practical missile-turbine blade can be made by either method of fabrication. In addition, useful data were obtained on root geometry for future application to light-weight rotor design.

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Blades with Sheet-Metal Airfoils

It was found that airfoils made from L-605 and Hastelloy B met the requirements. Airfoils made from A-286 proved to be susceptible to cracking.

A satisfactory method of fabrication consisted of forming the two sides of an airfoil separately and joining them by welding along the leading and trailing edges. The results of tests made with airfoils formed from a tubular shape indicated that this method is applicable only to certain materials because of extreme bending. Hastelloy B was superior to L-605 in this respect. Heat-treatment at various stages during forming might result in improved blade life.

The airfoil tips were closed by brazing or welding a thin cap. Either technique was satisfactory.

Attaching the airfoil to the base by brazing proved to be considerably more reliable than a welded joint. There were no failures in properly brazed attachments; none of the welded joints survived 30 hours.

Some investigation was made of the effect of thickness in the airfoil walls. It was observed that 0.030 inch was a lower limit for practical purposes, even in the tip region of tapered walls. This was determined with L-605 airfoils and may be assumed generally true for most materials on the basis of structural rigidity and resistance to fatigue. Airfoils with wall thicknesses of 0.022 and 0.025 inch failed in less than the required time; the failures were ascribed principally to fatigue.

The data obtained on special root fastenings in this phase of the 3563
investigation indicated that the supports would have to be brought nearer the center of the blade platform.

Cast Blades

The results of the investigation indicate some superiority of HS-21 over X-40 as a blade material for missile application. The HS-21 test blades were still intact after 30 hours of engine operation; many of the X-40 blades failed in fatigue. It was noted, however, that heat-treatment and shot-peening of the root resulted in improvement in the X-40 blades.

The root modification used for cast-blade specimens was found to be satisfactory as a means of blade retention and well adapted to a light-weight rotor installation. It was observed during inspection after engine operation, however, that incipient cracks were forming in the root serrations.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 3, 1954

REFERENCES

1. Morgan, W. C., and Morse, C. R.: An Experimental Investigation of Hollow Turbine Blades for Expendable Jet Engines. NACA RM E53L17, 1954.

2. Peaslee, Robert L., and Boam, Willard M.: Design Properties of Brazed Joints for High-Temperature Applications. Welding Jour., vol. 31, no. 8, Aug. 1952, pp. 651-662.

TABLE I. - NOMINAL COMPOSITIONS OF MATERIALS INCLUDED IN HOLLOW-BLADE INVESTIGATION

Alloy	C	Cr	Ni	Co	Mo	W	Ti	Fe	Other
L-605	--	20.0	10.0	51	--	15.0	--	--	
Hastelloy B	0.10	--	64.0	--	28.0	--	--	0.6	
A-286	.05	15.5	26.0	--	1.3	--	1.9	Bal.	Mn-1.4 Si-0.9 Va-0.3 Al-0.2
HS-21	.30	27.0	2.5	62	5.5	--	--	.1	
X-40	.50	24.3	10.5	55	--	7.5	--	.1	

TABLE II. - VARIATIONS AMONG BLADE GROUPS

Group number	Material					Airfoil wall thickness, in.								Material before forming			Base platform		Root type	
	L-605	Hastelloy B	A-286	HS-21 (cast)	X-40 (cast)	0.022	0.025	0.030	0.030 to 0.020	0.035 to 0.025	0.040 to 0.020	0.050 to 0.030	0.055 to 0.030	Flat stock	Tubular stock	Tapered stock	Contoured stub	Flat surface	Standard	Modified
1	x							x						x				x		x
2	x							x						x				x	x	
3	x							x						x			x			x
4	x							x						x			x		x	
5	x						x							x			x		x	
6	x					x								x			x		x	
7	x							x						x				x	x	
8	x							x							x		x		x	
9		x						x							x		x		x	
10			x					x						x			x		x	
11	x								x							x	x		x	
12	x									x						x	x		x	
13	x										x					x	x		x	
14	x											x				x	x		x	
15					x								x							x
16					x								x						x	
17					x								x							x
18				x									x							x

Group number	Root finish		Airfoil to base attachment			Brazing method		Brazing temperature		Braze material		Heat treatment		Blade tip		
	Shot peened	As machined	Brazed	Welded	Integral	Vacuum furnace	Salt bath	2075° F 15 min	2100° F 5 min	Nicrobraz	Nicrobraz 5 percent Ni	Improve properties	Stress relieve	Brazed cap	Welded cap	Open end
1		x		x											x	
2		x		x											x	
3		x	x			x		x			x				x	
4		x	x			x		x			x			x		
5		x	x			x		x			x				x	
6		x	x			x		x			x				x	
7		x	x			x		x			x				x	
8		x	x			x		x			x		x		x	
9		x	x			x			x	x			x		x	
10		x	x				x		x	x			x		x	
11		x	x			x			x	x			x		x	
12		x	x			x			x	x			x		x	
13		x	x			x			x	x			x		x	
14		x	x			x			x	x			x		x	
15		x			x											x
16		x			x											x
17	x				x							x				x
18		x			x											x

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TABLE III. - HEAT TREATMENT OF X-40 HOLLOW TURBINE BLADES
IN ARGON ATMOSPHERE

1	Heat to 500° F in short time
2	Increase temperature to 1350° F at a rate of 100° F per hour
3	Allow blades to remain at 1350° F for 16 hours
4	Increase temperature to 1500° F at a rate of 100° F per hour
5	Allow blades to remain at 1500° F for 4 hours
6	Allow blades to cool to room temperature in furnace

Figure 1. - Example of die-forming of pressure side of sheet-metal airfoils.

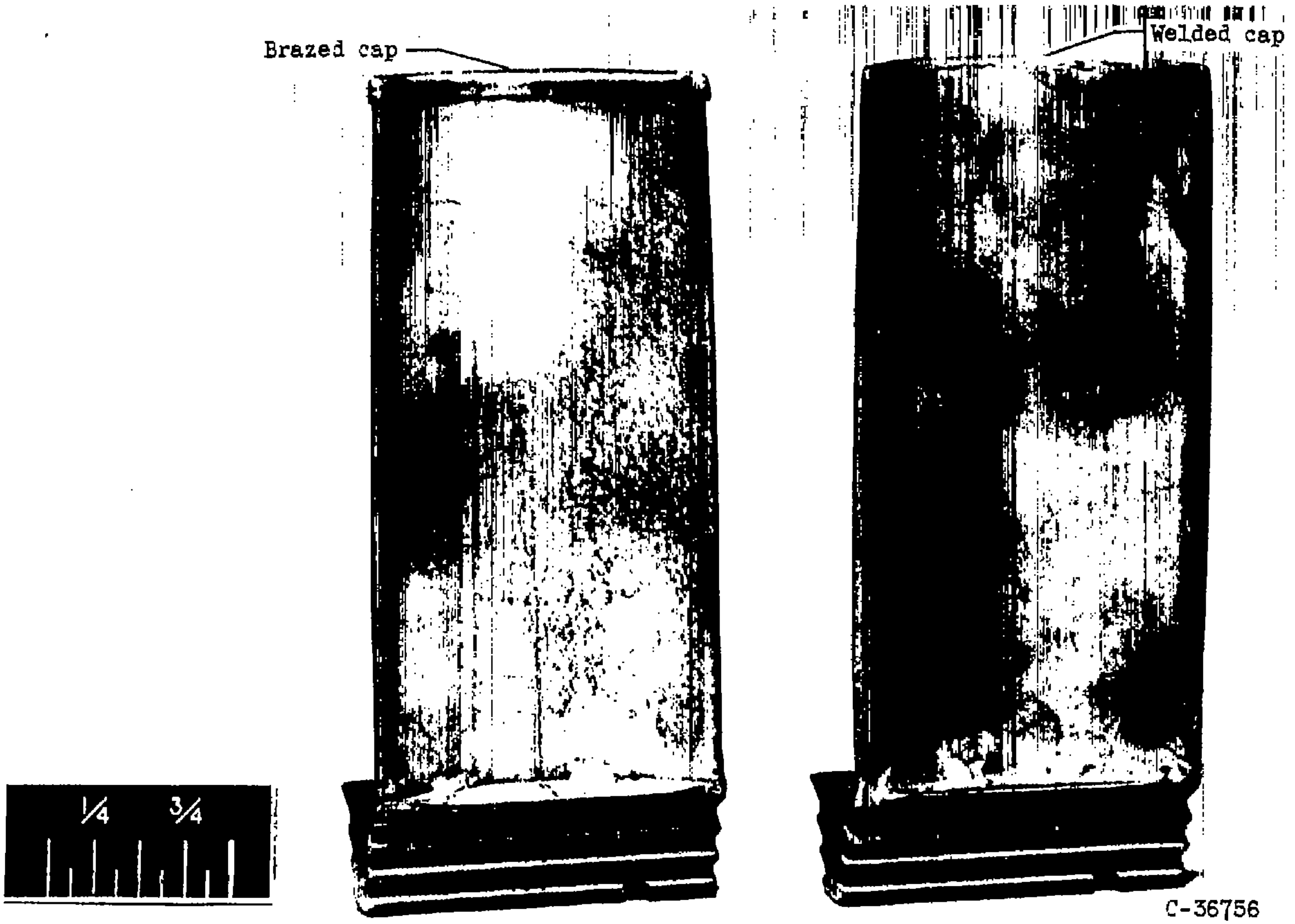
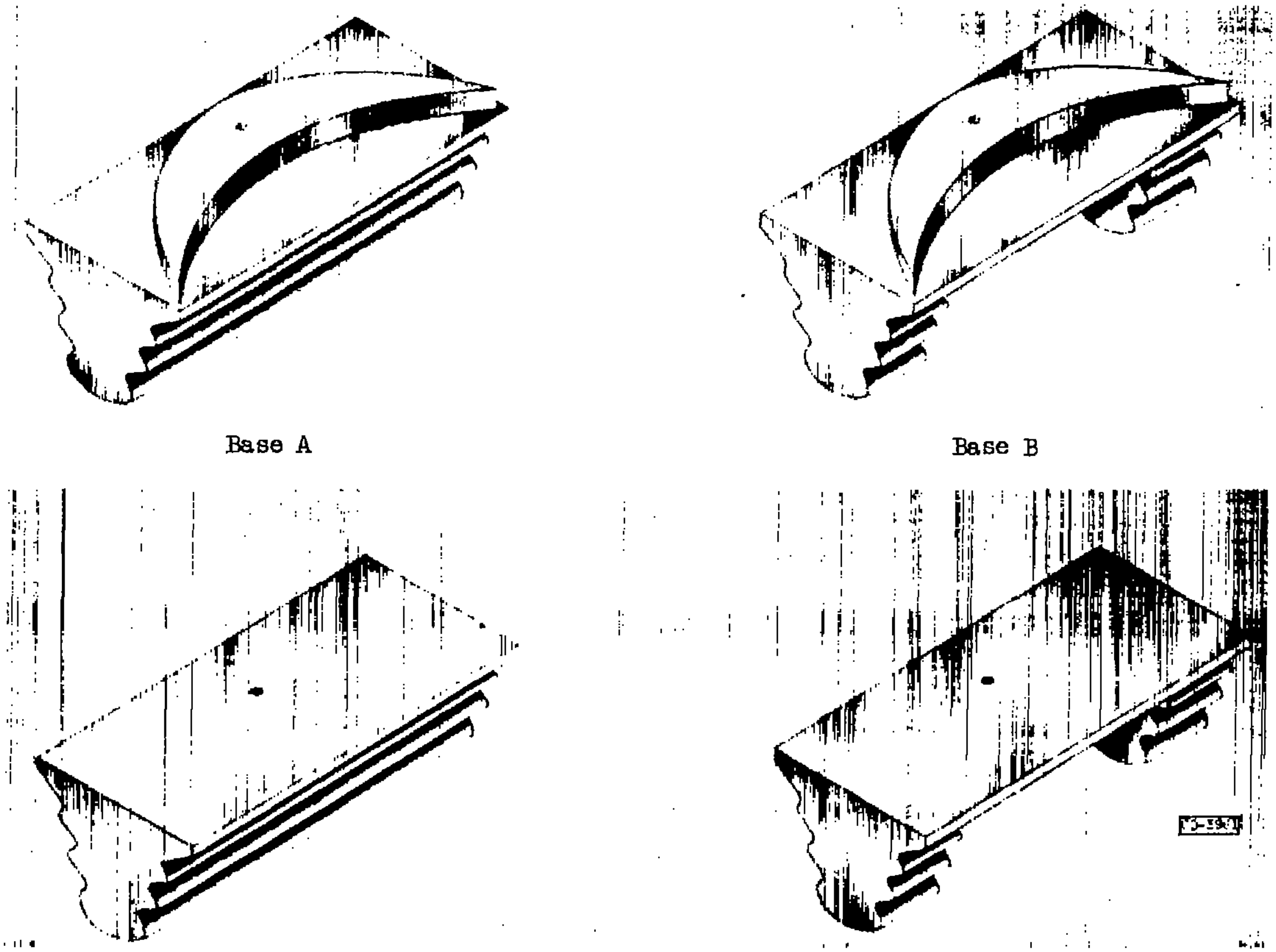


Figure 2. - Comparison between brazed and welded blade-tip caps.



Base A

Base B

Base C

Base D

Figure 3. - Four variations of bases used with sheet-metal airfoils.

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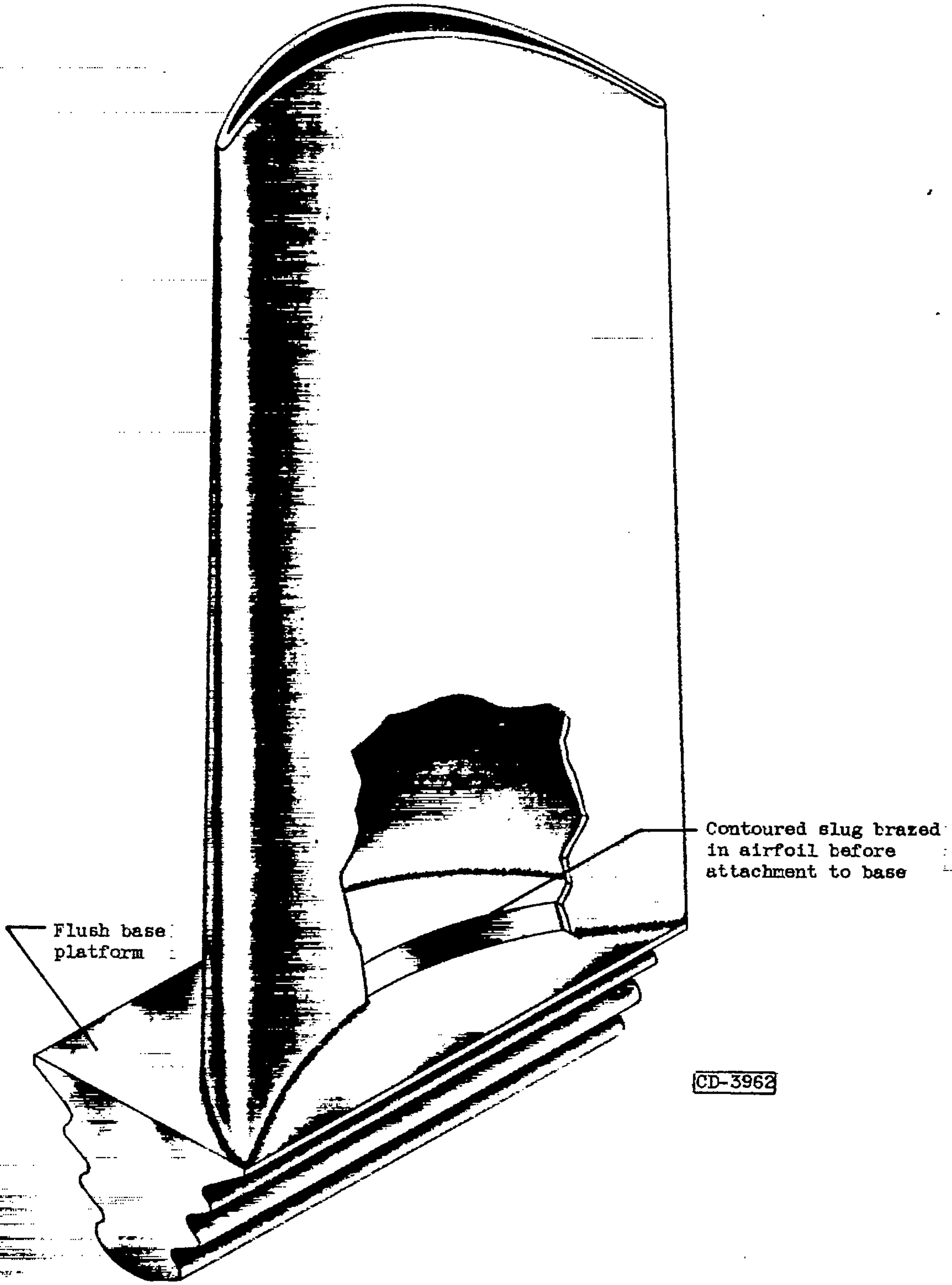

Figure 4. - Construction of sheet-metal airfoil brazed to flush base platform.

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Figure 5. - Fixture used in maintaining the correct relationship between sheet-metal airfoil and base platform during tack-welding prior to welding or brazing.

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CG-3 back

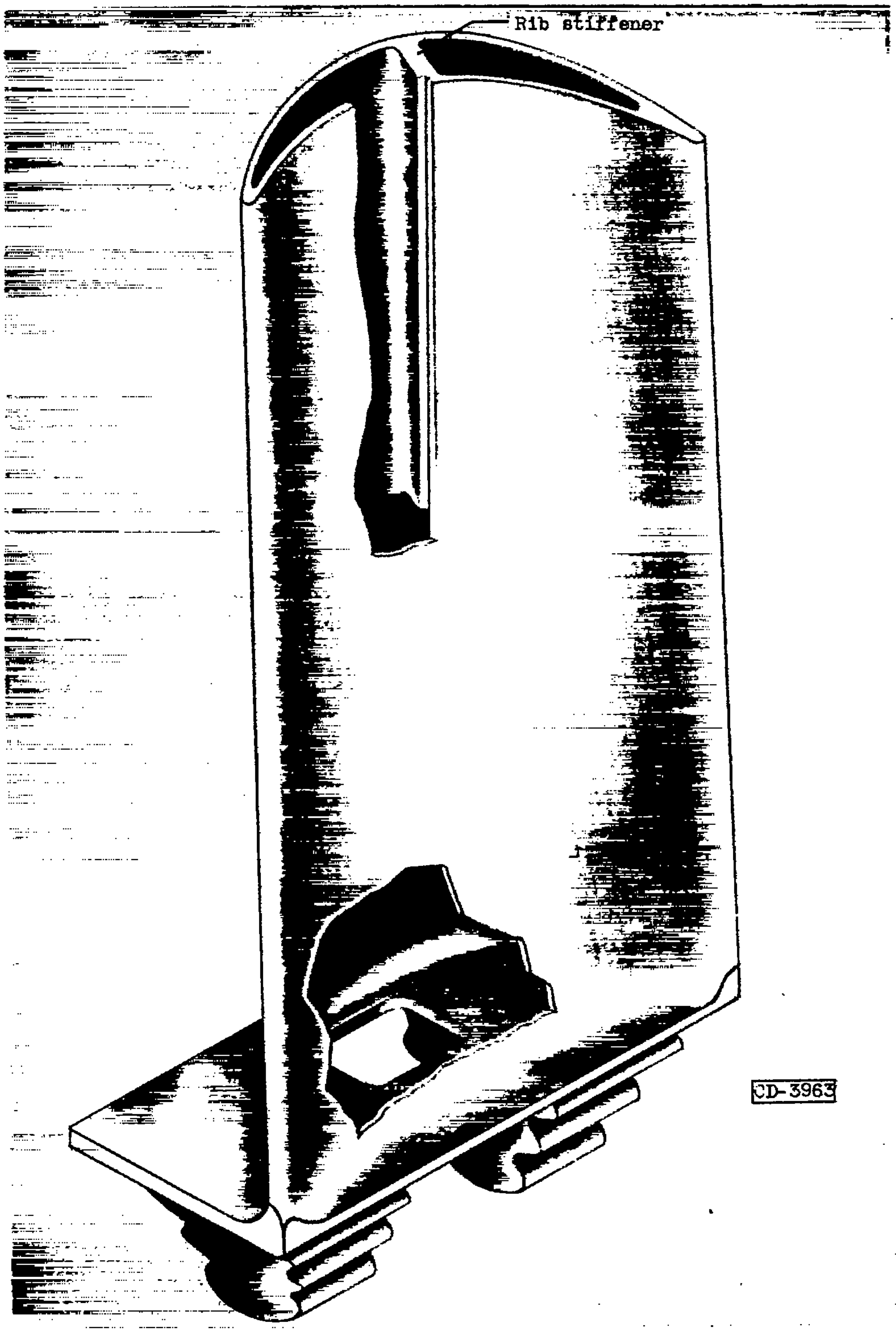

Figure 6. - Details of cast hollow blade with integral root.

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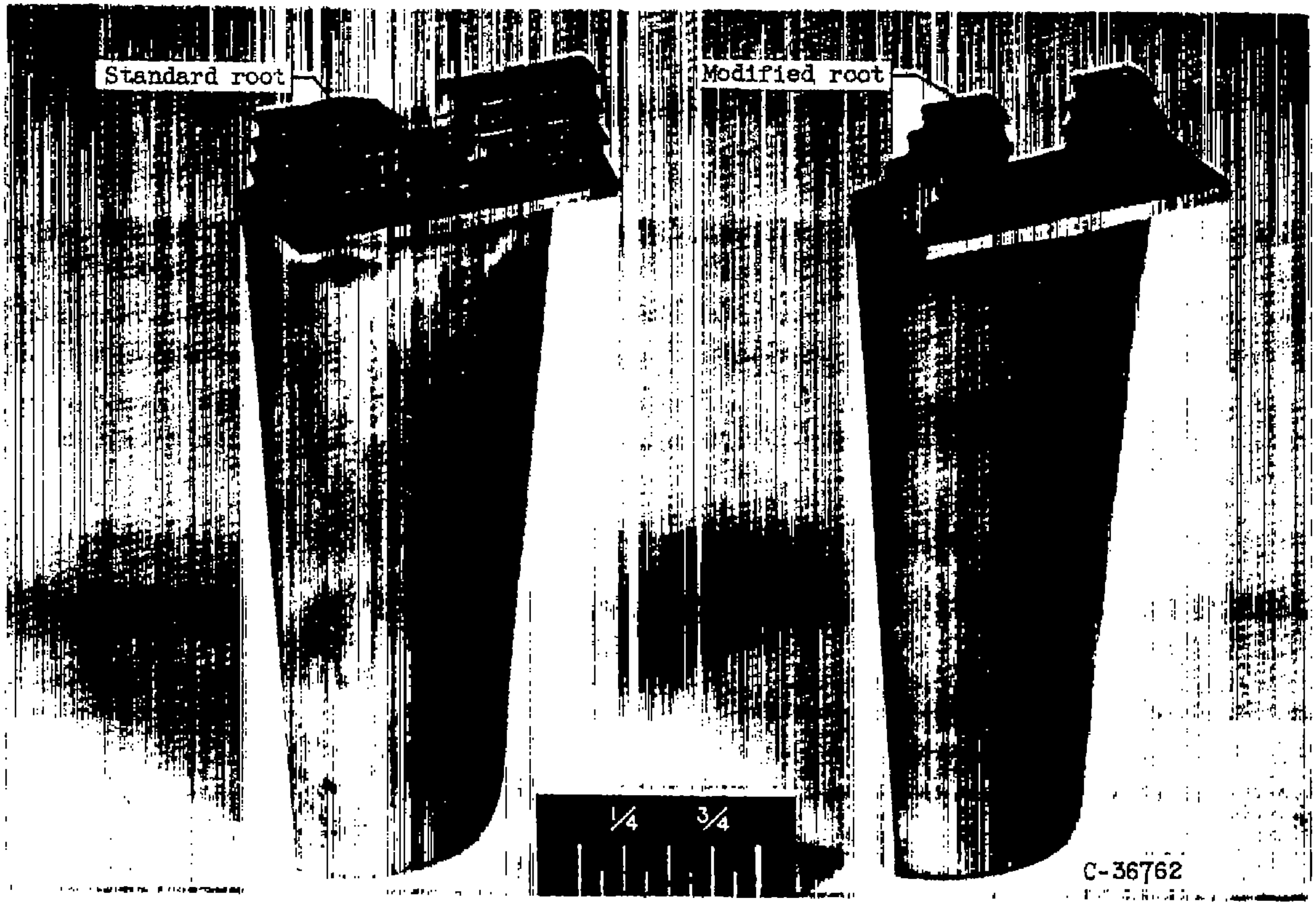

Figure 7. - Standard and modified root shapes of cast hollow turbine blades.

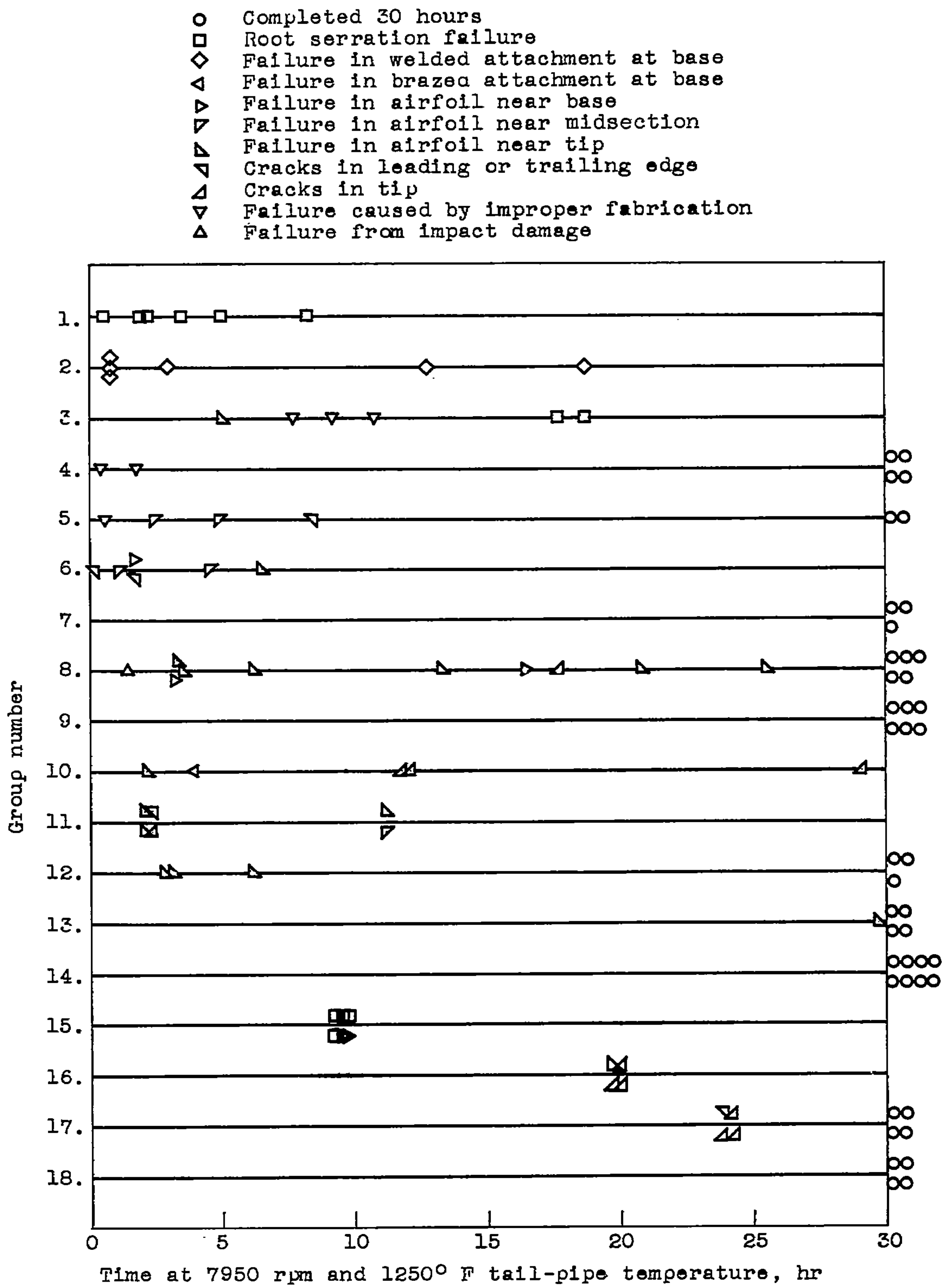

Figure 8. - Results of engine operation of 18 hollow-blade design variations.

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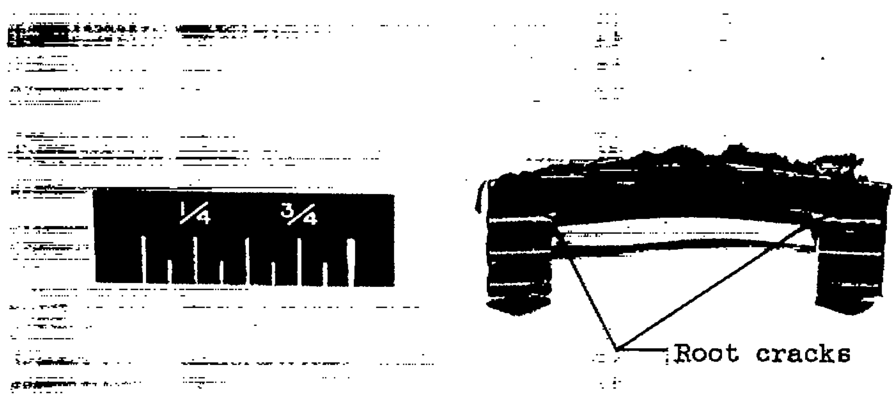

Figure 9. - Failure of Group 1 sheet-metal blade showing the excessive base deformation and location of root cracks.

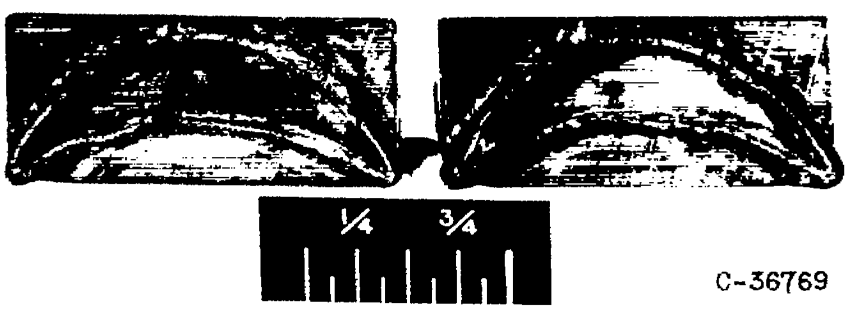

Figure 10. - Two failures of Group 2 sheet-metal blades showing the imperfect weld penetration.

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Figure 11. - Complete root failure produced by deformation of Group 3 sheet-metal blade.

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Figure 12. - Premature failure of Group 4 sheet-metal blade caused by excessive clearance between surfaces to be brazed.

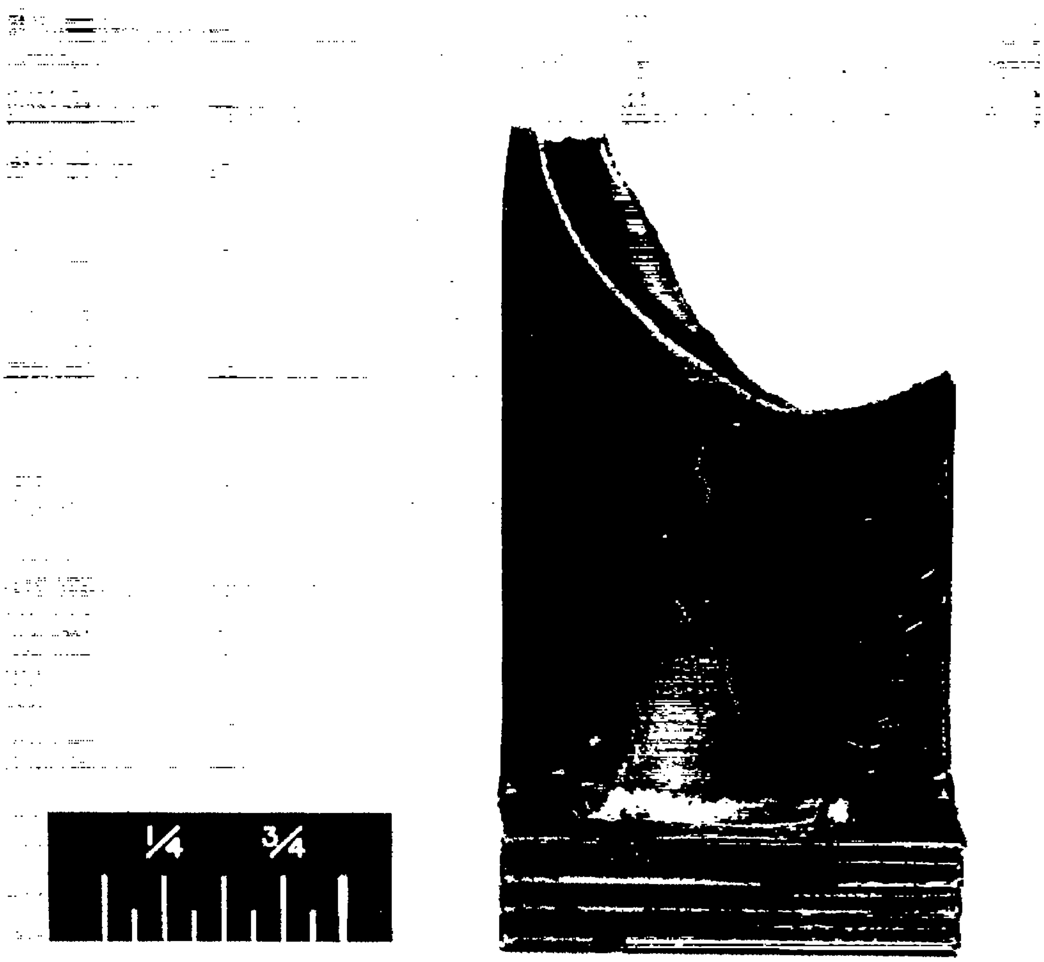

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Figure 13. - Mid-section airfoil failure in Group 5 sheet-metal blade suspected to have been caused by fatigue.

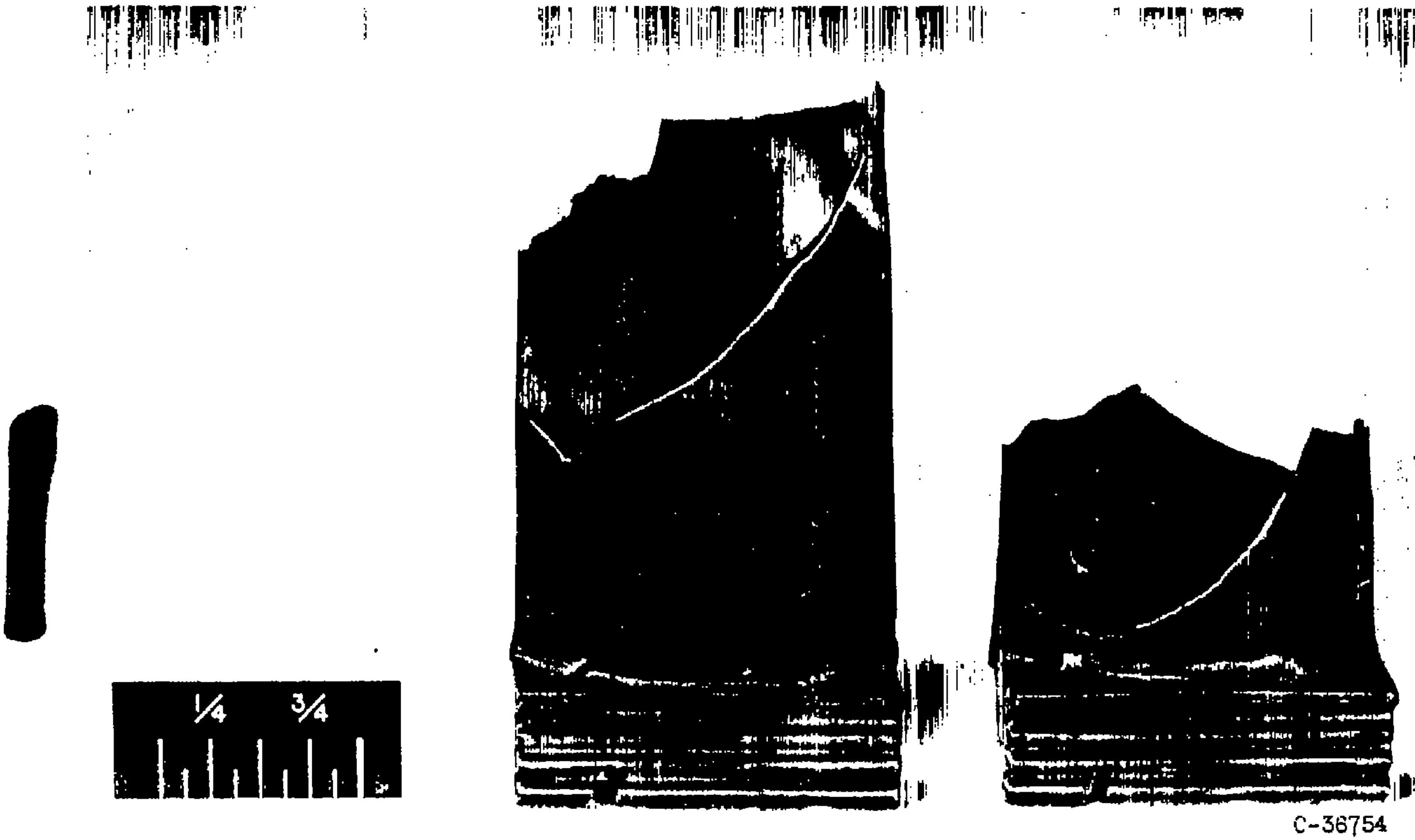

Figure 14. - Typical failures of Group 6 sheet-metal blades suspected to have been caused by fatigue.

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Figure 15. - Airfoil failures of Group 8 sheet-metal blades attributed to cracking caused by the forming operation and to imperfect edge brazing.

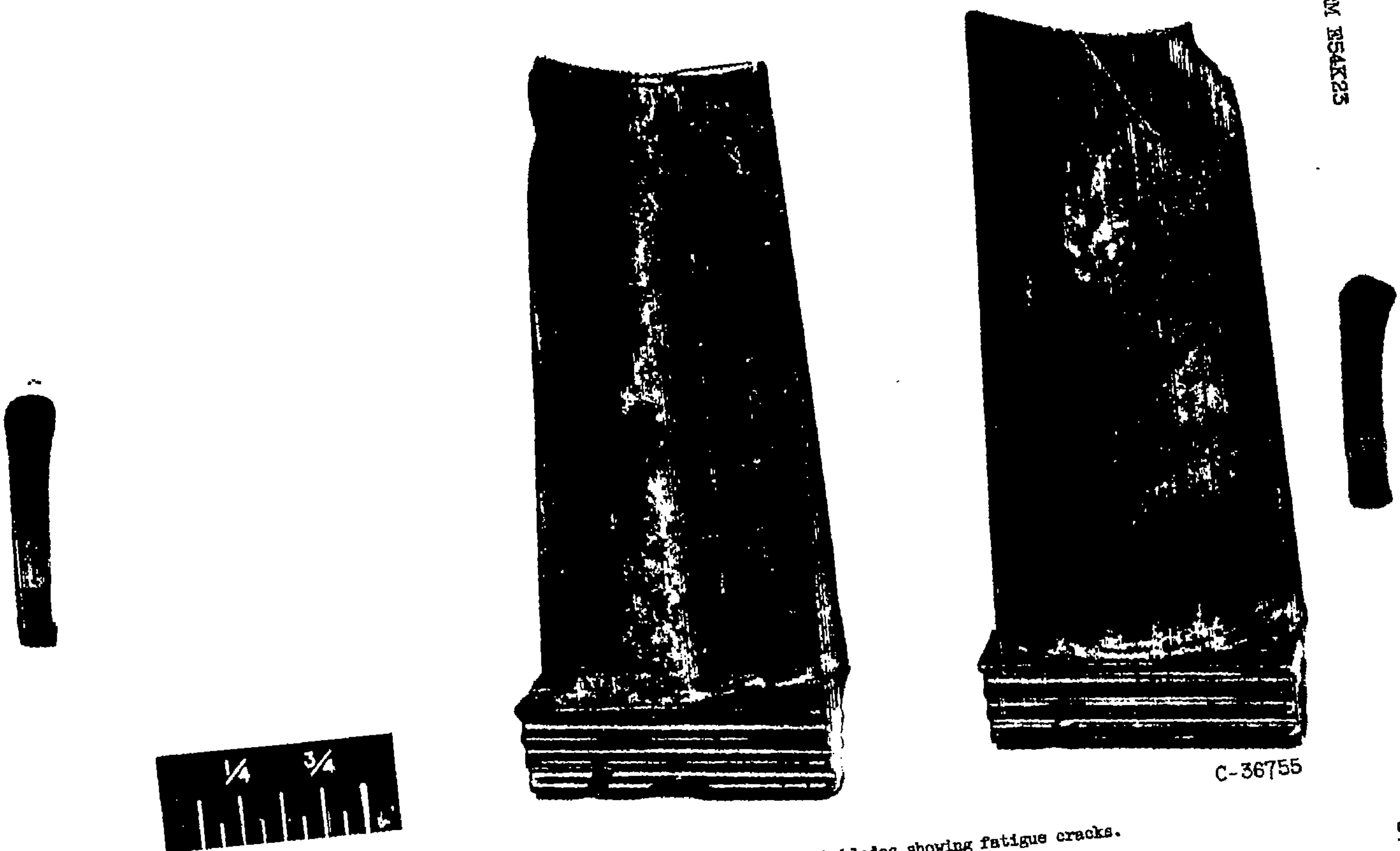

Figure 16. - Tip failure in Group 10 sheet-metal blades showing fatigue cracks.

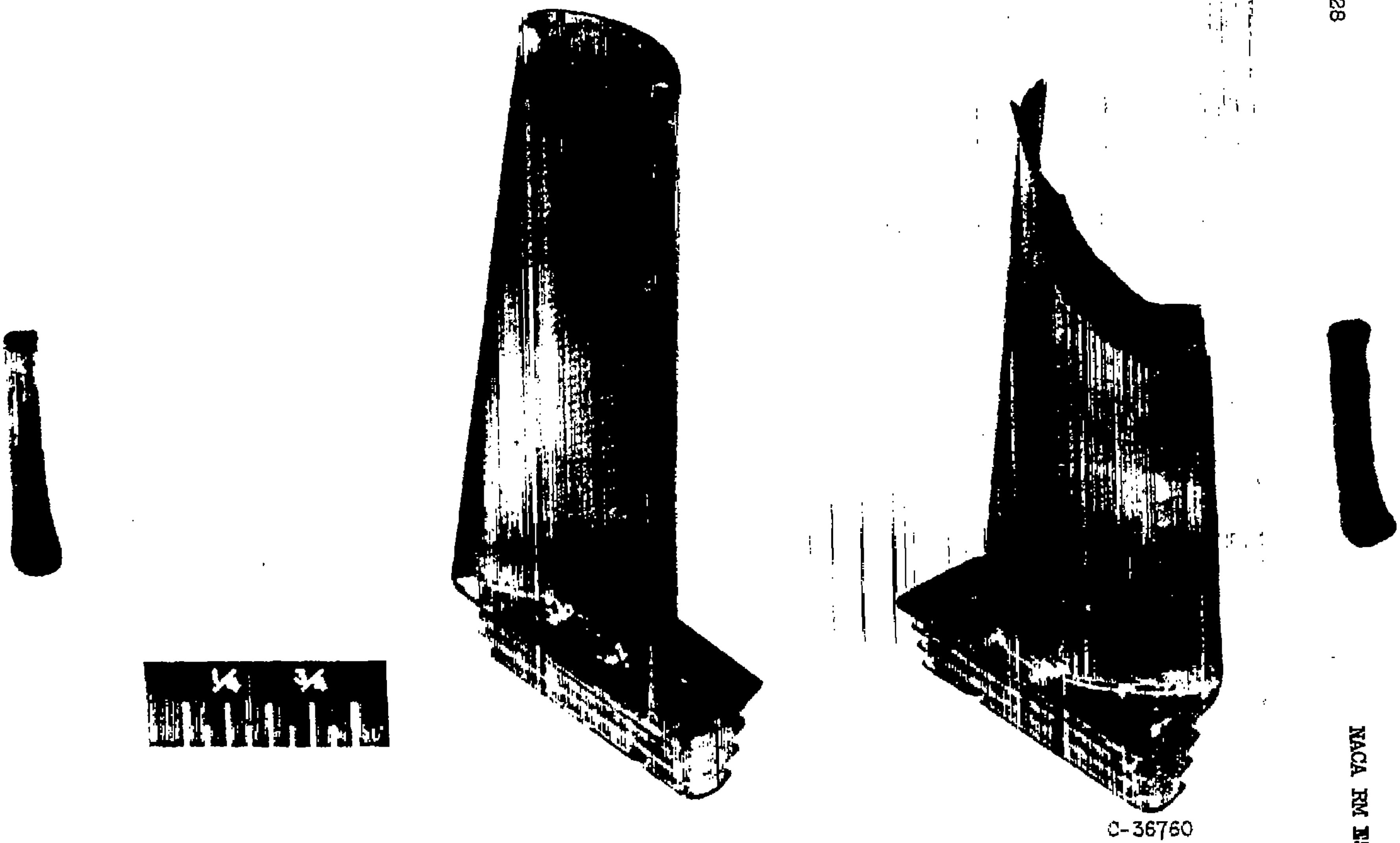

Figure 17. - Fatigue failures in Group 11 tapered-wall sheet-metal blades. (0.030-.020-in wall)

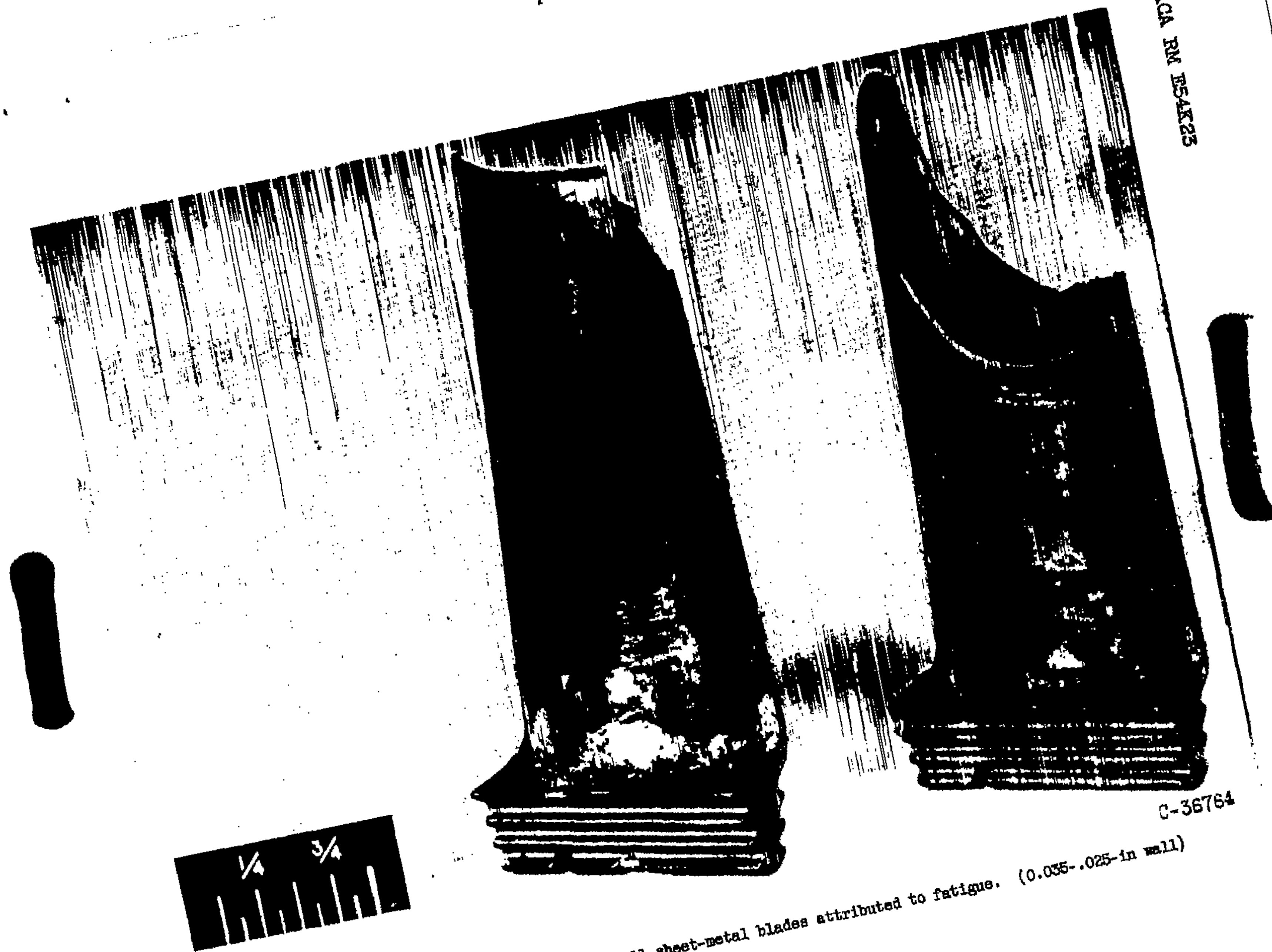

Figure 18. - Failures in Group 12 tapered-wall sheet-metal blades attributed to fatigue. (0.035-.025-in wall)

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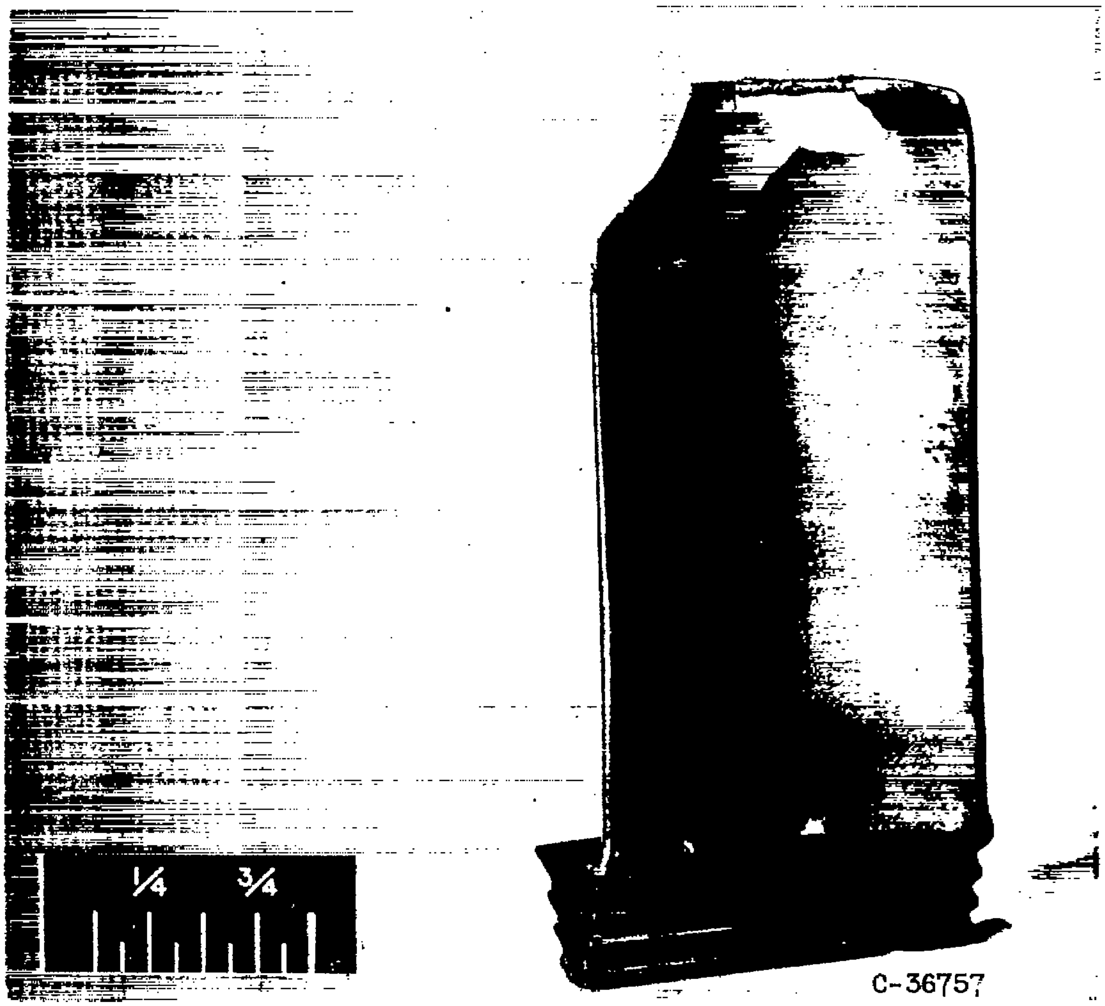

Figure 19. - Group 13 tapered-wall sheet-metal blade failure attributed to fatigue. (0.040-.020-in wall)

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Figure 20. - Root serration failure in a Group 15 hollow X-40 cast blade with a modified root.

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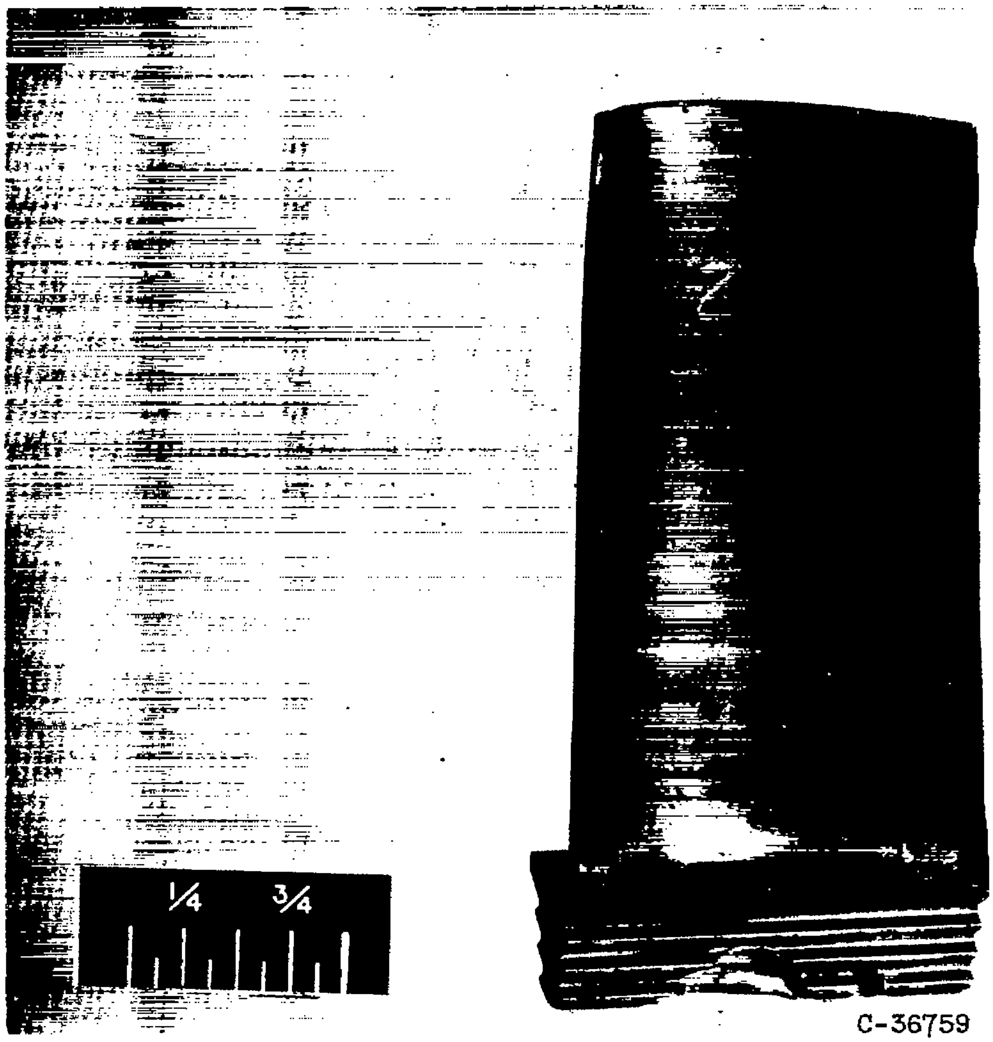

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Figure 21. - Fatigue crack in a Group 16 hollow X-40 cast blade.

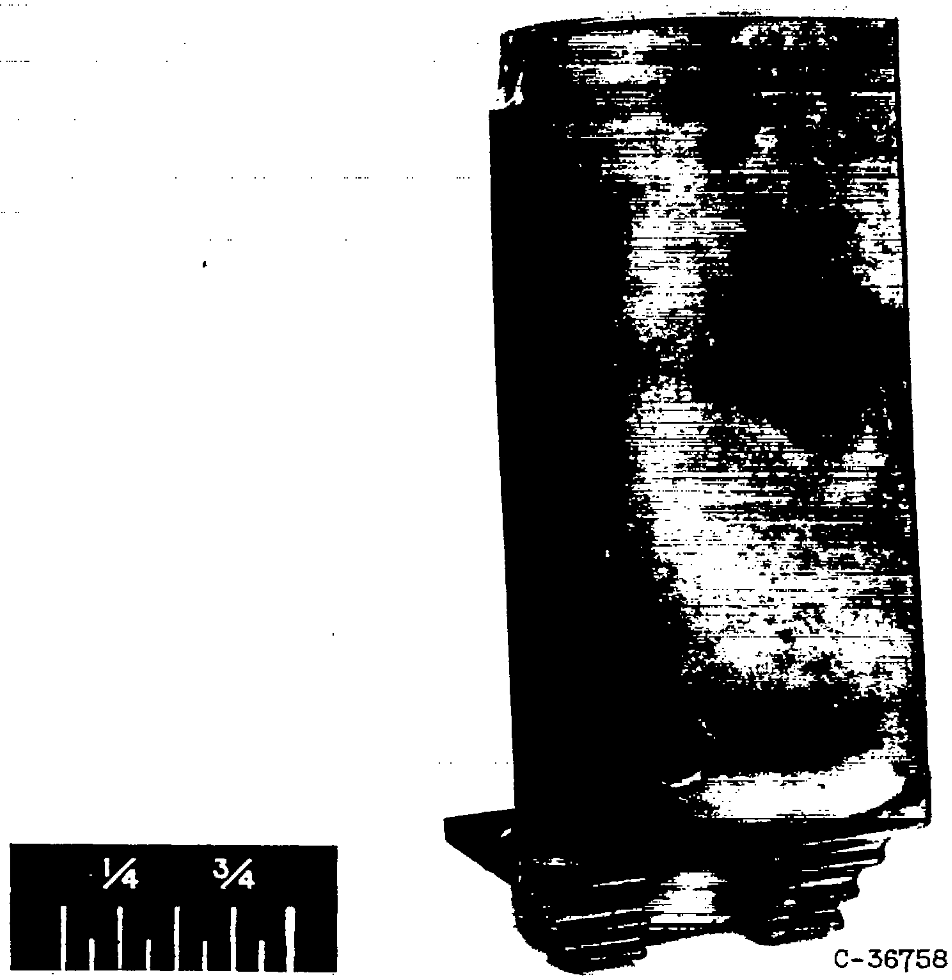

Figure 22. - Fatigue failure in the tip of a Group 17 hollow X-40 cast blade that had been heat treated and shot-peened in the root section.